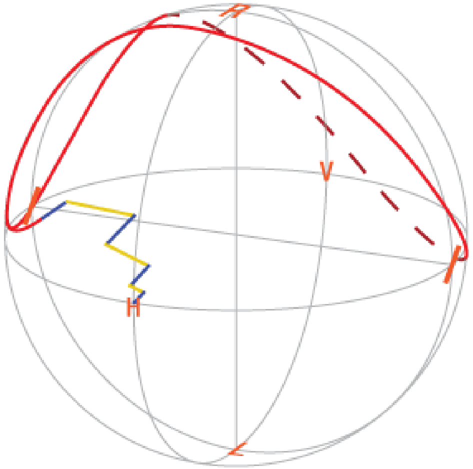
Fiber Paddle Controllers: Achieving Distinct Polarization States

- Three-paddle polarization controllers can be used to provide output light with a specific polarization state.
- Obtaining the desired polarization state can be challenging when, as is the case in this work:
    - The input polarization state is not known.
    - The exact change in polarization state provided by each paddle differs from the ideal.
- An approach, which is described in these slides, was developed to obtain a desired polarization state under these conditions.



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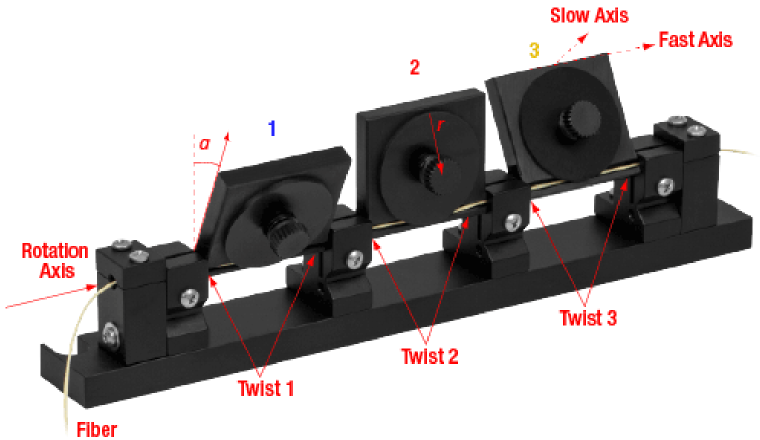
Background

- A Fiber Polarization Controller (FPC) creates stress-induced birefringence within single mode (SM) fiber to modify the output polarization state[1].
- When the fiber is coiled in the paddle's circular track the bending creates stress-induced birefringence is created.
- Rotating a paddle rotates the polarization.



Bending the fiber around in a number of loops (*N*) about the coil diameter (*D*) creates bend-induced retardation:

$$\delta = 2\pi^2 aN \frac{d}{\lambda D}^2$$

where *a*, λ, and *d* are the fiber photo-elastic coefficient, wavelength, and fiber diameter, respectively.[1]

Twisting regions of fiber by rotating a paddle by angle τ rotates the polarization by an angle:

$$\theta = \alpha\tau$$

where $\alpha = -n^2 p_{44}$ is based on the elasto-optical coefficients p_{44} of the fiber and refractive index n of the core.[2]

- Here we report our examination of the changes in the fiber's output polarization state as we bend and twist the fiber with a paddle-based polarization controller. We then outline a procedure to achieve any desired polarization state.

[1] R. Ulrich, S.C. Rashleigh, and W. Eickhoff, "Bending-induced birefringence in single-mode fibers" Opt. Lett. **5**, 273-275 (1980).

[2] R. Ulrich, A. Simon, "Polarization optics of twisted single-mode fibers" Appl. Opt. **18**, 2241-2251 (1979).

Loop Configuration

- The retardance provided by a single paddle depends on the length of fiber coiled in the paddle. The length is the circumference of the track multiplied by the number of loops.
- Each paddle can only accept a whole number of loops.
- The number of loops on each individual paddle is generally chosen to provide behavior approximately similar to a λ/4 or λ/2 wave plate.
- Fig. 1 shows a theoretical plot for the retardance as a function of the number of loops at 1310 nm and 1550 nm.
- At 1310 nm, and using FPS030 polarization paddles, λ/4 and λ/2 wave plates will be achieved using 1.2 and 2.8 loops, respectively.
- For this work, and according to standard practice, 2 loops were coiled in the first paddle, 3 in the second, and 2 in the third.
- Using these numbers of loops, none of the paddles is expected to perform perfectly as a λ/4 or λ/2 wave plate at 1310 nm.

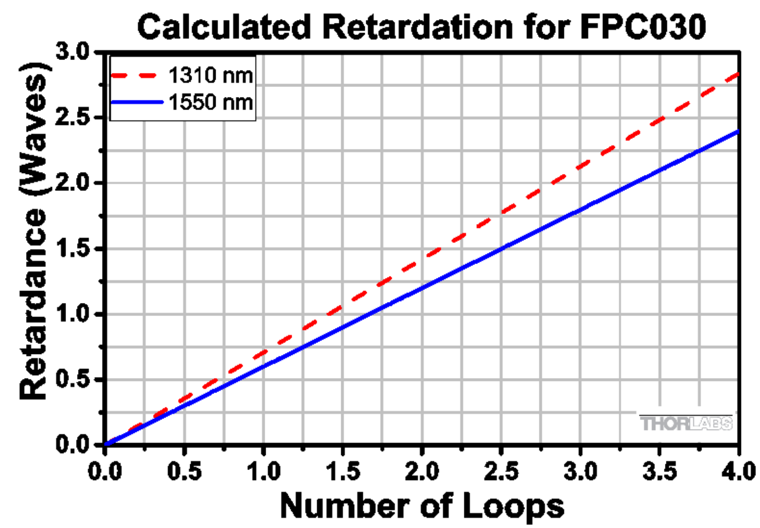
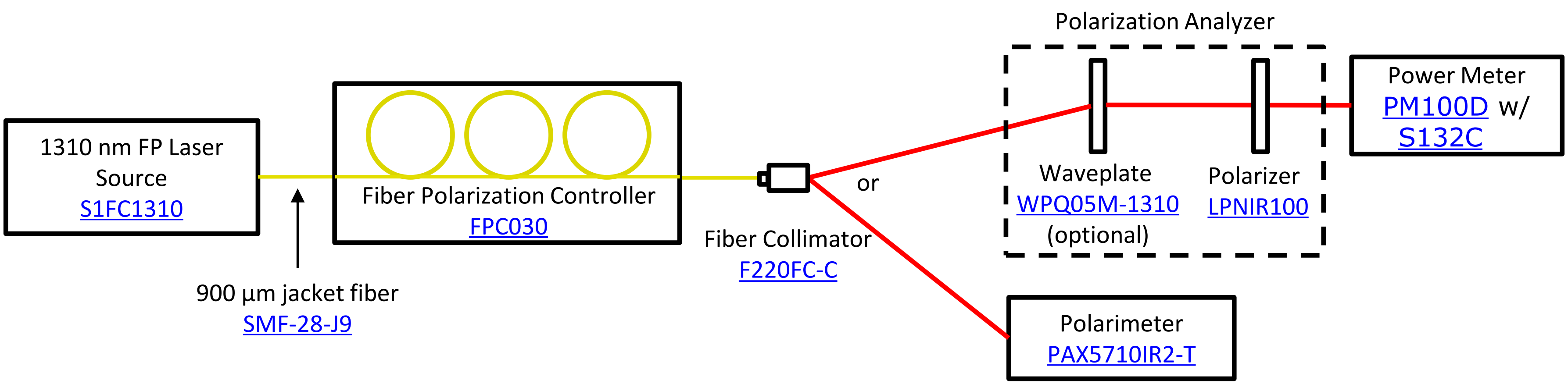


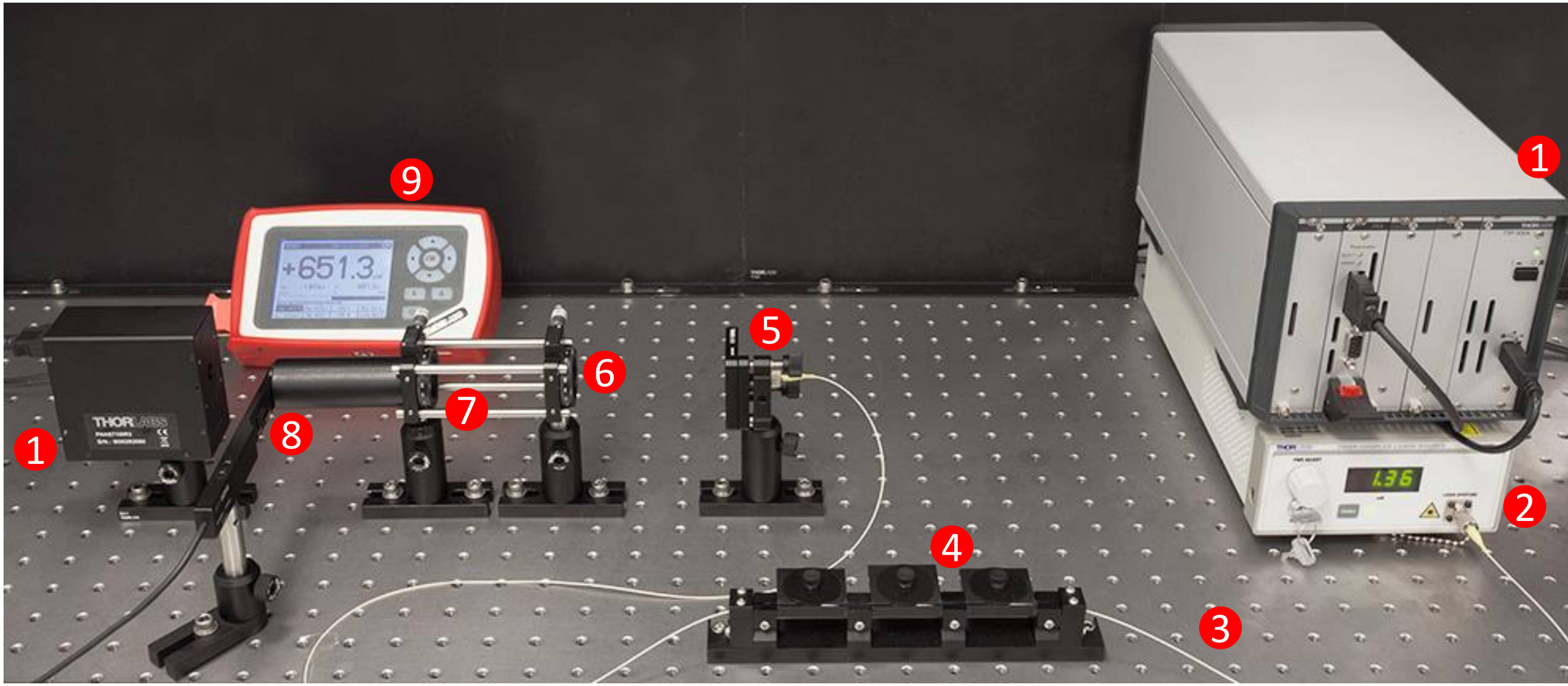
Figure 1: Theoretical retardation vs. the number of loops for 1310 nm and 1550 nm.

Experimental Design

- A 1310 nm laser (S1FC1310), with arbitrary output polarization was coupled into a polarization paddle (FPC030) that was pre-loaded with SMF28e+ fiber using a 2-3-2 loop configuration.
- The output of the fiber paddle was coupled into a fiber collimator (F220FC-C) and the free space beam passed through either a polarization analyzer or Polarimeter.
- The polarimeter (PAX5710IR2-T) provided a visualization of the polarization change to create a better understanding of the change created by the paddles.
- The analyzer was set up for either linear (single polarizer) or circular (polarizer and wave plate) polarization and the output was monitored on a power meter to create a desired output polarization state orthogonal to the analyzer.



Experimental Setup

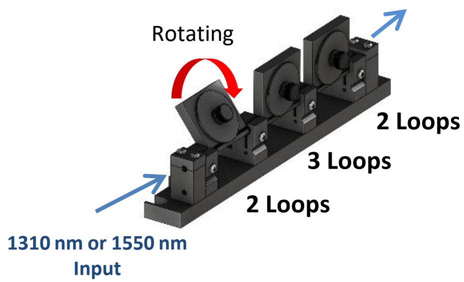


1) 1000 – 1250 nm Polarimeter: PAX5710IR2-T
2) 1310 nm Benchtop Laser Source: S1FC1310
3) SMF-28e+ SM Fiber: SMF-28-J9
4) Fiber Polarization Controller: FPC030
5) Fiber Collimator: F220FC-C
6) 1310 nm Quarter-Wave Plate: WPQ05M-1310
7) 650 – 2000 nm Linear Polarizer: LPNIR100
8) 700 – 1800 nm Photodiode Power Sensor: S132C
9) Power and Energy Meter Console: PM100D

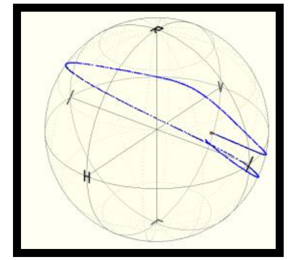
Results – Visualizing Polarization Change

- Polarization change was visualized for both a 1310 nm and a 1550 nm input while rotating each paddle individually within a 2-3-2 loop configuration.
- All three paddles started in the fixed, vertical position and then each paddle was articulated through its full travel range while the other two remained in their starting, vertical positions.
- The 2-loop paddles provided displacement predominantly in the vertical direction (between the circular polarization poles).
- The 3-loop paddle provided displacement predominantly in the horizontal direction (parallel to linear polarization equator).

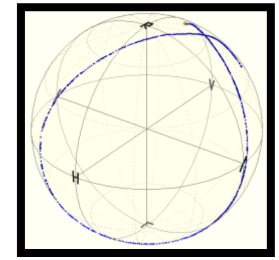
Fiber Paddle 1



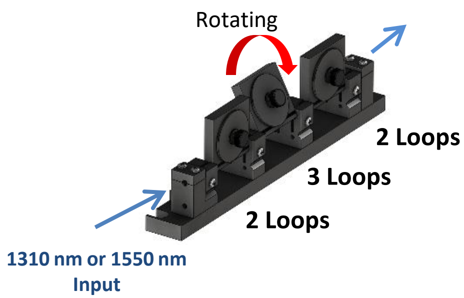
1310 nm Output



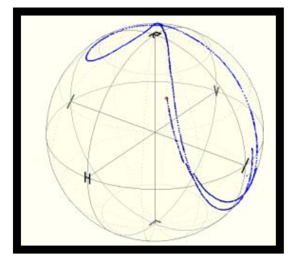
1550 nm Output



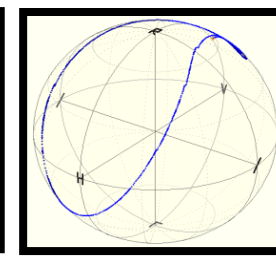
Fiber Paddle 2



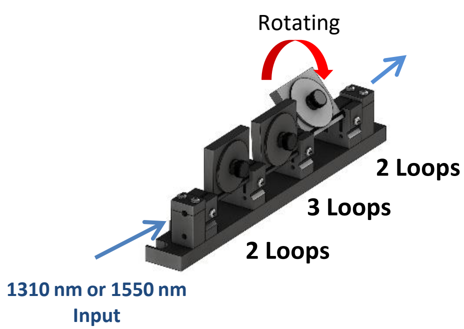
1310 nm Output



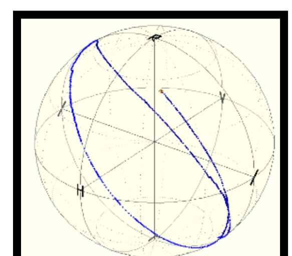
1550 nm Output



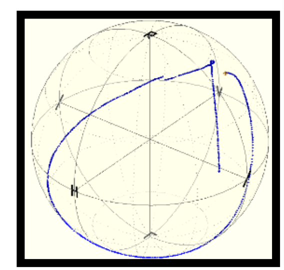
Fiber Paddle 3



1310 nm Output



1550 nm Output



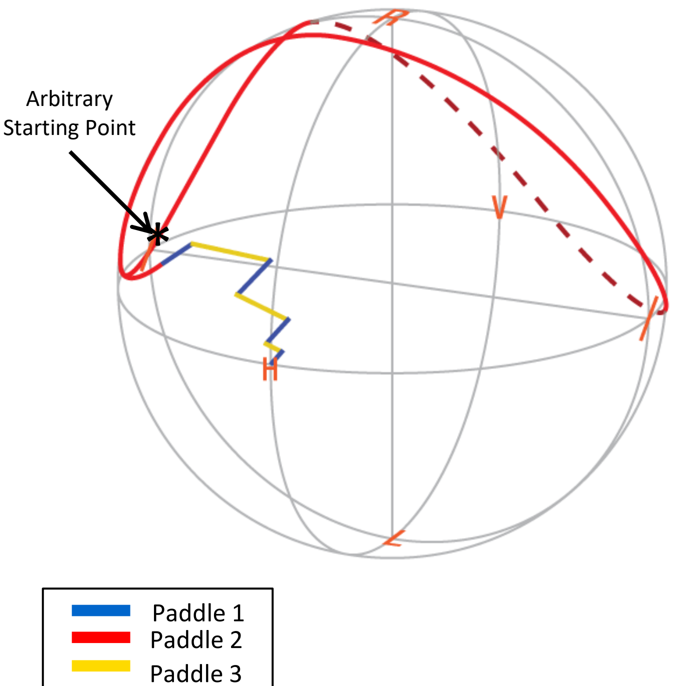
Procedure to Create Desired Polarization State

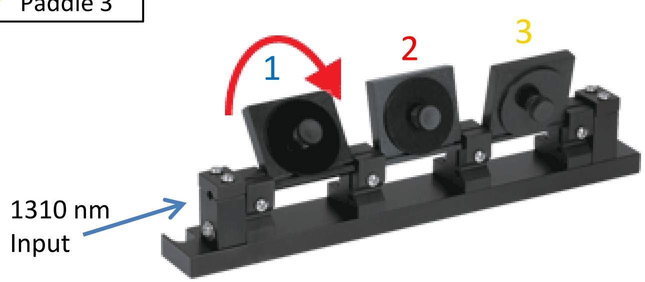
- After visualizing the polarization change, we developed a procedure to convert the arbitrary input polarization state to any of the four distinct linear polarization states (horizontal, vertical, and ±45˚) and two circular states (right and left hand circular).

- While it is relatively straightforward to find a polarization state with a Polarimeter, we created the procedure using an analyzer and power meter for more general use:
    1. Measure the total power out of the polarization controller P_0 with a power meter.
    2. Direct the output beam (after the polarizer controller) through a polarization analyzer. The analyzer should be aligned orthogonal to the desired polarization state. For example:
        i. Vertical polarization: linear polarizer transmission axis must be horizontal.
        ii. Right-handed circular polarization: light passes through a quarter-wave plate and then a linear polarizer with the transmission axis of the polarizer 45˚ CCW with respect to the wave-plate fast axis looking in the direction of propagation of the beam.
    3. Rotate the half-wave fiber paddle (middle paddle) across the full range while monitoring the output power through the analyzer P_r. Leave the paddle fixed at the location of minimum power for the remainder of the procedure.
    4. Use the two adjacent quarter-wave fiber paddles individually (only one at a time) until a lower minimum has been observed at the power meter. This will generally require numerous iterations to reach the desired polarization extinction ratio (P_r / P_0).

- If the desired Polarization Extinction (PE) ratio has not been achieved, the user can try adjusting the middle paddle and/or start over from the beginning to ensure they are not stuck at a local minimum. In our testing, we achieved a PE ratio of 1,000:1 (-30 dB).

Power Minimization Visualization





- Here we created a visualization of the polarization change during the power minimization technique[1].
- The red trace shows the change due to the 2nd paddle, with 3 fiber loops, as it was rotated. When the minimum power was found, the paddle was left in position (no further adjustment applied).
- Power was further lowered by iteratively rotating the 1st paddle, with 2 fiber loops, shown by the blue trace, and the 3rd paddle, also with 2 fiber loops, shown by the yellow trace.
- The iterative process created the crisscross of blue and yellow traces seen on the Poincaré sphere until the global minimum (-30 dB polarization extinction ratio) was achieved. In this case, the minimized power corresponds to linear horizontal polarization because the analyzer was aligned to vertical polarization.

[1]While this figure was created from real data, we had to swap the polarimeter and analyzer to find the true minimum and then connect the minimum power location with the end point of the previous iteration for demonstration purposes. Actual path and number of iterations are dependent on various parameters (see next slide).

Experimental Limitations

- All measurements were recorded at room temperature with the fiber taped to the optical table. It is possible for environmental effects to change the output polarization state, such as temperature variations and vibration.

- The LPNIR100 polarizer within the analyzer provides a polarization extinction (PE) ratio of >100,000:1 at 1310 nm and 1550 nm. It is important to remember that an economy polarizer with a lower PE ratio, or a premium polarizer with a higher PE, could provide a lower or higher PE ratio when measuring the output polarization.

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Summary

- Measurements were recorded to examine the changes in polarization state when using a three-paddle fiber polarization controller (FPC031).
- Experimental results show:
  - Paddles with 2 and 3 numbers of loops did not behave exactly as λ/2 or λ/4 wave retarders.
  - For the 1st and 3rd paddles, with 2 fiber loops, displacement was predominantly in the vertical direction (between circular polarization poles).
  - The 2nd paddle, with 3 fiber loops, displaced the polarization predominantly in the horizontal direction (parallel to linear polarization equator).
- A procedure was created to achieve a free-space polarization state after the polarization controller using an analyzer aligned to the orthogonal state and a polarization extinction ratio of 1,000:1 (-30 dB).